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SOME EFFECTS OF COMPOSITION ON FRICTION AND WEAR OF GRAPHITE-FIBER-REINFORCED POLYIMIDE LINERS IN PLAIN SPHERICAL BEARINGS

by Harold E. Sliney and Thomas P. Jacobson

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SUMMARY

A plain spherical bearing design with a ball diameter of 28.6 millimeters and a 1.6-millimeter-thick, molded composite liner was evaluated. The liner material is a self-lubricating composite of graphite-fiber-reinforced polyimide resin (GFRPI). The liner is prepared by transfer molding a mixture of one part chopped graphite fiber and one part partially polymerized resin into the space between the bearing ball and the outer race and then completing the polymerization under heat and pressure. Several liner compositions were evaluated: Two types of polyimide, condensation and addition; two types of graphite fiber, low and high modulus; and four powder additives - cadmium oxide (CdO), cadmium iodide (CdI_2), graphite fluoride ($\text{CF}_{1.1}\text{n}$), and molybdenum disulfide (MoS_2). The bearings were oscillated ± 15 degrees at 1 hertz for 20 kilocycles under a radial load of $2.8 \times 10^7 \text{ N/m}^2$ (4000 psi) in dry air at 25° , 200° , or 315° C .

Both types of fiber and polyimide gave low friction and wear. Friction and wear were high during "run-in" but stabilized at lower values during the rest of the test. A simple equation was developed to fit the wear-time data. After 20 kilocycles, radial clearance was 1.5×10^{-5} to 8.1×10^{-5} meter (0.6×10^{-3} to 3.2×10^{-3} in.) and averaged 3.3×10^{-5} meter (1.3×10^{-3} in.) at all temperatures. Friction decreased as temperature increased: Stabilized friction coefficients averaged 0.15 at 25° C , 0.10 at 200° C , and 0.06 at 315° C .

The GFRPI composites lubricated the bearings well except when they were completely dry - either degassed in vacuum or exposed for many days to dry air and then tested in dry air. Under these conditions, additives were helpful: CdO and CdI_2 reduced wear, and $\text{CF}_{1.1}\text{n}$ reduced friction. At 25° C , MoS_2 reduced friction at loads above $7.0 \times 10^7 \text{ N/m}^2$ (10 000 psi) - to a friction coefficient of 0.10 at 10^8 N/m^2 (14 000 psi).

INTRODUCTION

Self-lubricating composites of polymers with various solid lubricant powders and other fillers or reinforcing fibers are an important class of bearing material. Thermoplastic polymers such as the acetals and polyamides are commonly used partly because they are conveniently formed by injection molding (refs. 1 and 2). Molybdenum disulfide (MoS_2) and graphite powders, which are often used as fillers to reduce friction, usually weaken the structure. Graphite fiber fillers, on the other hand, both lubricate and reinforce (ref. 3). The graphite-fiber-reinforced thermoplastics can therefore provide both good lubrication and high strength.

Aeronautics and general industrial applications of polymer composite bearing materials are increasing. One important use of polymer composites is for self-lubricating liners in plain spherical, oscillating bearings. In aircraft, plain spherical bearings are used extensively throughout the airframe as control surface bearings and as pivot bearings in hydraulically actuated, mechanical linkages. They are also used in actuator linkages for engine controls.

Because of the aerodynamic heating in supersonic aircraft, airframe bearings with upper temperature limits above 300°C are needed. Engine control bearings can also be exposed to high temperatures from the engine. Most polymers in current use are limited to service temperatures below 260°C . For higher temperatures, a more thermally stable polymer such as a polyimide can be used. Although the self-lubricating behavior of polyimides with a graphite powder filler has been known for some time (refs. 4 to 6), tribological studies of graphite-fiber-reinforced polyimides (GFRPI) are a more recent development (refs. 7 to 9). Polyimide materials can be used at light loads to perhaps 390°C (ref. 6), but for high loads and long duration the temperature limit is about 300° to 340°C for those polyimides evaluated so far as bearing materials (ref. 10).

A preliminary study of GFRPI composites in plain spherical bearings showed the feasibility of using this composite as the ball material in such bearings (ref. 8). For fiber contents to 60 weight percent, the best combination of strength and tribological properties was achieved with a fiber-resin weight ratio of approximately 1. Later work (refs. 10 and 11) showed that the dynamic unit load capacity of a plain spherical bearing with a GFRPI ball is about $7.0 \times 10^7 \text{ N/m}^2$ (10 000 psi) at 25°C and about one-half that value at 340°C . Plain cylindrical bearings with thin-wall GFRPI liners had a higher load capacity than a plain spherical bearing with a GFRPI ball, $2.8 \times 10^8 \text{ N/m}^2$ (40 000 psi), at 25°C - with only a moderate decrease at higher temperatures. Therefore, GFRPI alone may be used as the ball material in plain spherical bearings for light to moderate loads, but higher loads require a metal ball and a GFRPI-lined outer race.

Experimental, GFRPI-lined, plain spherical bearings were designed at NASA

Lewis and made by a bearing manufacturer¹ who also developed the necessary molding and other fabrication procedures. Addition (A) and condensation (C) polyimides, as well as high-strength (H) and low-strength (L) graphite fibers, were compared. Also studied were the solid lubricant additives molybdenum disulfide (MoS_2) and graphite fluoride ($\text{CF}_{1.1}$)_n and the lubricating adjuvants cadmium iodide (CdI_2) and cadmium oxide (CdO). The effects of a vacuum degassing pretreatment and atmospheric moisture were determined.

Bearing tests were performed to determine wear and friction at 25^o, 200^o, and 315^o C. In most tests, the load was $2.8 \times 10^7 \text{ N/m}^2$ (4000 psi), but a few tests were run at unit loads to $1 \times 10^8 \text{ N/m}^2$ (14 500 psi). The balls were oscillated against the GFRPI liner at a frequency of 1 hertz and an amplitude of ± 15 degrees.

MATERIALS

The composites used in this study were made from a mixture of graphite fibers and polyimide resin at a weight ratio of 1. The fibers were chopped into lengths of 6.4×10^{-3} meter (0.25 in.) and were dispersed as randomly as possible throughout the polyimide matrix. (Although the fiber orientation was multi-axial, it probably was not perfectly random because some preferred ordering is likely during the molding process.) Two types of graphite fibers were evaluated. Typical properties are listed in table I. The fiber L had a low tensile strength and a low elastic modulus. The fiber H had a medium tensile strength and a high elastic modulus.

Two types of polyimide resins were also evaluated. Both were formulated to eliminate voids in the final cured polymer. Polyimide A was an addition polyimide that was highly crosslinked. Polyimide C was a condensation polyimide that was linear, amorphous, and essentially noncrosslinked.

Four combinations of these fibers and polyimides were evaluated: The addition polyimide with the low-modulus fiber (composite AL), the addition polyimide with the high-modulus fiber (composite AH), the condensation polyimide with the low-modulus fiber (composite CL), and the condensation polyimide with the high-modulus fiber (composite CH). In addition to these four materials, composites were prepared in which 10 percent (by weight) of either ($\text{CF}_{1.1}$)_n powder, CdI_2 powder, or CdO powder was added to the CH composites. Type CH composites with 16-percent ($\text{CF}_{1.1}$)_n or 20-percent MoS_2 were also made. These solid lubricant additives were incorporated into the polyimide/graphite-fiber mixture before polymerization.

The bearing ball and ring material was 440C high-temperature stainless steel hardened to Rockwell C60. The balls had a surface finish of 10^{-7} meter (4 μ in.). The

¹Marlin Rockwell Division of TRW, Jamestown, N. Y.

composite liner was 1.6 millimeters thick. The test bearing design, with additional relevant dimensions, is shown in figure 1.

MOLDING PROCEDURES

The liners were made by transfer-molding the polymer/graphite-fiber mixture into the space between the ball and race and then completing the polymerization under heat and pressure. The ball and race were mounted for accurate concentricity and functioned as the main elements of the mold. The ball was precoated with a mold-release to minimize adhesion between the ball and the composite. Molding procedures for mixtures with either the condensation or addition polymer are detailed in table II.

APPARATUS AND TEST PROCEDURE

Apparatus

The apparatus for testing self-aligning, plain spherical bearings is shown in figure 2. The test bearing was held in a housing that can be heated by an induction coil. The ball was oscillated ± 15 degrees at 1 hertz by a reciprocating hydraulic drive.

Test Procedure

The test procedure was as follows: A slight axial load was hydraulically applied to align the journal. The test load, a radial load to the test bearing, was pneumatically applied to the journal. The spherical bearing element (ball) was oscillated against the outer race. Friction force was measured by a preloaded piezoelectric load cell mounted in the drive arm. This signal, proportional to the tension and compression during the stroke, was recorded on a strip chart. Wear was measured by two methods: (1) Radial displacement of the journal as measured with a dial gage on the shaft assembly; and (2) bearing weight loss.

Since bearing weight changes were complicated by moisture adsorption and desorption, all pre- and post-test weighings were done after prolonged storage in the same atmosphere. Storage and weighings were repeated until the weight remained constant, to insure that equilibrium with the storage atmosphere had been achieved.

Two test sequences were used in this program: The first sequence involved testing each bearing, as received from the manufacturer, in dry air: first at 25⁰ C, then at 200⁰ C, and finally at 315⁰ C. The second involved degassing each bearing for 16 hours

in a vacuum of 100 millitorr at about 120⁰ C before testing it.

Wear Coefficient Calculation

The wear coefficient, wear volume per unit load per unit sliding distance, was calculated from both weight loss measurement and journal displacement. Wear volume was calculated both as the net weight loss divided by the composite density (1.5 g/cm³) and as the radial wear multiplied by the projected area of the bearing (28.6 mm diam by 12.7 mm length). These wear volumes were then divided by the bearing load and the sliding distances.

RESULTS AND DISCUSSION

Wear of GFRPI Composites without Additives

Experimental data. - The increase in radial clearance, as measured by journal displacement, during bearing oscillation are shown in figure 3 for the four base compositions at the three test temperatures: 25⁰, 200⁰, and 315⁰ C. Because the wear was widely scattered during the run-in period, arbitrarily taken as the first 2000 cycles, stabilized wear was defined as that occurring between 2 and 20 kilocycles of oscillation. The standard test duration was about 5.5 hours.

Total wear, run-in wear, and the calculated wear rates for both run-in and stabilized conditions are given in table III. Neither type of polyimide or filler gives a clear advantage. The average total wear depths for the four GFRPI composites are $(5 \pm 3) \times 10^{-5}$ meter at 25⁰ C, $(3 \pm 1) \times 10^{-5}$ meter at 200⁰ C, and $(5 \pm 1) \times 10^{-5}$ meter at 315⁰ C. However, since the same bearing was used progressively in testing first at 25⁰ C and then at 200⁰ and 315⁰ C, the effect of run-in predominated at 25⁰ C. Some of this run-in "wear" is probably due to compressive creep of the liner, as is substantiated by weight loss measurements, which are discussed later in this section.

Curve fitting of experimental data. - An algebraic expression of the form

$$y = aN^b \dots \quad (1)$$

can be fit to the wear data of figure 3 and table I. In this expression, y is radial wear depth, N is the number of bearing oscillations, and a and b are evaluated constants. The constants are determined by simultaneously solving equation (1) using the experimental values (table II) of radial wear y at N of 2 and 20 kilocycles. The constant a is the controlling term during early wear and equals y at N = 1 kilocycles. The constant

b assumes more importance at high values of N; for b much less than unity, steady-state wear rates are much lower than run-in wear rates.

Figure 4 gives calculated curves for CH liners at 25⁰ C and for AH liners at 315⁰ C, all at a 2.8×10^7 -N/m² (4000-psi) unit load. These curves were selected for this figure because they establish typical, but not extreme, upper and lower boundaries of wear for the composite liners at all three temperatures.

The equation for the upper wear curve is

$$y = 4.4 \times 10^{-5} N^{0.046} \text{ meter} \quad (2)$$

The equation for the lower wear curve is

$$y = 0.68 \times 10^{-5} N^{0.29} \text{ meter} \quad (3)$$

The data points at 2 and 20 kilocycles that were used to calculate the constants for equations (2) and (3) are shown in figure 4. The calculated curves were extended to N = 100 kilocycles. Wear data for six experiments, which were each run for 100 kilocycles, are superimposed on this figure. They all fall within the range predicted by the calculated curves.

Friction of GFRPI Composites without Additives

Friction coefficients measured during bearing oscillation are shown in figure 5 for the four GFRPI compositions at the three test temperatures. In general, friction coefficients initially were from 0.12 to 0.18. At 25⁰ C they remained relatively constant; but at higher temperatures they stabilized at lower levels: 0.08 to 0.12 at 200⁰ C, and 0.04 to 0.08 at 315⁰ C. This friction reduction may be associated with the transfer film that forms on the contacting metallic ball surface, lubricating wear debris trapped between the ball and the liner, and possibly the crystallographic orientation of graphite and polyimide at the sliding interface.

The beneficial effect of nonabrasive wear debris on subsequent sliding has been studied by Play and Godet (ref. 12). In their model, nonabrasive wear debris becomes compacted within the sliding contact and acts as a "third body" to supplement lubrication of the primary rubbing surfaces. This model appears to be applicable to GFRPI composite liners.

Wear of GFRPI Composites with Additives

Ten percent by weight of a powdered compound - either CdO, CdI₂, or (CF_{1.1})_n -

was added to CH composites (condensation polyimide and high-modulus graphite fiber). Cadmium oxide and cadmium iodide were chosen because they have long been known to improve lubrication of graphite in dry air (refs. 13 and 14). Graphite fluoride was chosen because it is an intercalation compound of graphite that has low friction and long endurance when used as a polyimide-bonded, dry film lubricant at temperatures to 315° C and above (ref. 15).

Wear-time data for these three composites are compared in figure 6 with the base composite at the three test temperatures. The wear data are summarized in table IV. The results show that the additives give no clear advantage under these bearing test conditions. In general, the wear of composites with additives fell within the band for base composites in figure 4 (1.5×10^{-5} to 5×10^{-5} m). The insensitivity of graphite-fiber-reinforced polymers to solid-lubricant additives has also been observed by Giltrow (ref. 14).

Average Wear Coefficients of GFRPI Composites

To consolidate the data, we averaged the wear of the four base composites and the CH composite with 10 weight percent of either CdO, CdI₂, or (CF_{1.1})_n for each of the three test temperatures (fig. 7). Coefficients calculated from weight loss data and from displacement measurements of equilibrium wear correlate well with each other. According to both methods, wear coefficients increase moderately with temperature in dry air: 8×10^{-11} , 15×10^{-11} , and 20×10^{-11} cm³/cm-kg at 25°, 200°, and 315° C, respectively. These data agree reasonably well with the bearing wear coefficient of 12×10^{-11} cm³/cm-kg reported in reference 10 for AL-type GFRPI composites tested in 25° C air with about 50-percent relative humidity. In that study, the temperature effect was even less: Wear coefficients were typically 12×10^{-11} cm³/cm-kg at both 25° and 315° C. In tests by Fusaro (ref. 7) involving 440C pins sliding on GFRPI disks in air of 50-percent relative humidity, the wear coefficients for GFRPI composites were $(13 \pm 4) \times 10^{-11}$ cm³/cm-kg at 25° C and $(15 \pm 3) \times 10^{-11}$ cm³/cm-kg at 300° C.

Friction with GFRPI Composites Containing Additives

The continuous friction coefficient - time data for the CH composite containing 10 weight percent of either CdO, CdI₂, or (CF_{1.1})_n are compared in figure 8 with data for the base composite at the three test temperatures. In no case did the additives reduce friction and in some cases they significantly increased it. However, the friction coefficients did not exceed about 0.19.

Several bearings were also tested with composite liners that contained more

(CF_{1.1})_n - 16 weight percent - or 20-weight-percent MoS₂. In these experiments the effect of load on friction was studied. Some preliminary data are shown in figure 9. Of the three materials (the base composite and the two composites with an additive), friction was lowest for the base composite at loads to about 3.9×10^7 N/m² (5500 psi). At higher loads, the (CF_{1.1})_n additive reduced friction slightly. The MoS₂ additive gave lower friction than the base composite at loads above about 7.0×10^7 N/m² (10 000 psi). That MoS₂ reduces friction with load is well known (refs. 16 to 18). Therefore, it may be a desirable additive to GFRPI composites for very high load applications, but it does not show any beneficial effect at lighter loads.

Bearing Pretreatment and Moisture Effects

Adsorbed moisture usually enhances the lubricating properties of self-lubricating composites that contain a substantial amount of graphite (refs. 19 and 20). However, as previously discussed, the GFRPI composites were not adversely affected by testing in dry air. This observation and the lack of additive response raised the question of whether the residual adsorbed moisture in the as-received bearings might be functioning as a beneficial additive. To answer this, we pretreated a set of bearings in a vacuum oven (100 millitorr at 120° C) to degas them and then tested them in dry air (20-ppm H₂O) and in vacuum.

Figure 10 shows the combined effects of bearing pretreatment and atmospheric moisture on the friction and wear of GFRPI composites without additives at 25° C. The degassing pretreatment increased both friction and wear when the bearings were tested in dry air. The increase was even greater when the bearings were tested in vacuum. However, when the pretreated bearings were tested under ambient humidity conditions (30- to 50-percent relative humidity), friction decreased with test time and wear was low (about the same as for the as-received bearings tested in dry air). Thus, some moisture is rapidly readsorbed from the ambient air although (as water adsorption studies have shown) adsorption equilibrium is achieved very slowly. Conversely, the desorption that takes place during testing of as-received bearings in dry air is not sufficient to affect bearing friction and wear. (Material must be exposed for over a week in a dry air to achieve desorption equilibrium (ref. 10).) Therefore, both a degassing pretreatment and a very dry test atmosphere are required to deteriorate the lubricating properties of GFRPI at 25° C.

We then determined the effect of additives on degassed bearings in dry air at 25° C. The friction and wear data are given in figure 11. The (CF_{1.1})_n additive reduced friction but increased wear. The CdO and CdI₂ additives only slightly reduced friction but considerably reduced wear.

We concluded that GFRPI composites are self-lubricating under all but the most ex-

treme moisture-free conditions at 25° C. Even under those conditions, CdO or CdI₂ are helpful in restoring the self-lubricating characteristics of the composite.

SUMMARY OF RESULTS

Composites made of graphite-fiber-reinforced polyimide (GFRPI) with a fiber-resin ratio (by weight) of about 1 were evaluated as molded outer-race liners in plain spherical bearings. Several compositions were studied: two types of polyimide (addition and condensation polymers), two types of graphite fiber (high and low modulus), and four powder additives (CdO, CdI₂, (CF_{1.1})_n, and MoS₂). Friction and wear were measured during oscillation (± 15 deg at 1 Hz) at three temperatures: 25°, 200°, and 315° C. The main results were as follows:

1. All compositions provided good lubrication in dry air: After run-in, all compositions at 25°, 200°, and 315° C, respectively, had wear coefficients of 8×10^{-11} , 15×10^{-11} , and 20×10^{-11} cm³/cm-kg and average friction coefficients of 0.15, 0.10, and 0.06.

2. Despite individual differences in the lubrication behavior of the various compositions, neither type of polyimide or graphite fiber nor the additives gave a clear advantage.

3. Only under extremely dry conditions, when the bearings were first vacuum degassed and then tested in dry air or vacuum, did lubrication behavior deteriorate. Under these conditions, CdO and CdI₂ additives reduced friction and wear.

4. Wear rates (as determined by the rate of increase in bearing radial clearance) were always higher during run-in, before conditions stabilized. Wear equations were developed which defined a scatter band that fit the 20-kilocycle test data and adequately predicted wear to at least 100 kilocycles.

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TABLE I - TYPICAL PROPERTIES OF GRAPHITE FIBERS

Property	Fiber L ^a	Fiber H ^b
Tensile strength, N/m ² (lb/in ²)	6.2×10 ⁸ (9.0×10 ⁴)	2.0×10 ⁹ (2.8×10 ⁵)
Elastic modulus, N/m ² (lb/in ²)	3.0×10 ¹⁰ (5.0×10 ⁶)	3.9×10 ¹¹ (5.7×10 ⁷)
Length, cm (in.)	0.64 (0.25)	0.64 (0.25)
Diameter, μ m (mil)	8.4 (0.33)	6.6 (0.26)
Specific gravity	1.4	1.4

^aLow tensile strength and low elastic modulus.^bMedium tensile strength and high elastic modulus.TABLE II - PROCEDURES FOR MOLDING GRAPHITE-FIBER-REINFORCED
POLYIMIDE BEARING LINERS

Procedure	Liner composition	
	Graphite-fiber-reinforced condensation polymers	Graphite-fiber-reinforced addition polymers
Mixing fibers and polymer precursor solution	Ambient	Ambient
Drying (solvent evaporation)	4 hr; 200° C	1 hr; 200° C
Precuring (B-stage polymerization)	15 hr; 230° - 260° C	1 hr; 230° C
Molding ^a	10 min; 430° C; 6.9×10 ⁷ N/m ² (10 000 psi)	1 hr; 320° C; 6.9×10 ⁷ N/m ² (10 000 psi)
Postcuring	4 hr; 260° C	4 hr; 200° C

^aHold under pressure and cool to 260° C before releasing mold.

TABLE III. - WEAR DATA FOR GRAPHITE-FIBER-
REINFORCED COMPOSITES
[Fiber-resin weight ratio, 1.]

(a) SI units

Test temperature, °C	GFRPI composition code ^a	After 2 kilocycles (run-in)	After 20 kilocycles (total)	0 - 2 kilocycles (run-in)	2 - 20 kilocycles (stabilization)
		Wear (as determined from journal displacement ^b), μm		Wear rate, $\mu\text{m/kilocycle}$	
25	AL	15	33	8	1.0
	AH	71	81	36	.6
	CL	38	48	19	.6
	CH	46	51	23	.3
200	AL	25	25	13	<0.1
	AH	13	38	6	1.4
	CL	20	33	10	.7
	CH	13	15	6	.1
315	AL	^c 38	53	19	0.8
	AH	28	41	14	.7
	CL	38	41	19	.2
	CH	41	56	21	.8

(b) U.S. customary units

Test temperature, °F	GFRPI composition code ^a	After 2 kilocycles (run-in)	After 20 kilocycles (total)	0 - 2 kilocycles (run-in)	2 - 20 kilocycles (stabilization)
		Wear (as determined from journal displacement ^b), mil		Wear rate, mils/kilocycle	
85	AL	0.6	1.3	0.30	0.04
	AH	2.8	3.2	1.40	.02
	CL	1.5	1.9	.75	.02
	CH	1.8	2.0	.90	.01
400	AL	1.0	1.0	0.50	<0.01
	AH	.5	1.5	.25	.06
	CL	.8	1.3	.40	.03
	CH	.5	.6		.01
600	AL	^c 1.5	2.1	0.75	0.03
	AH	1.1	1.6	.55	.03
	CL	1.5	1.6	.75	.01
	CH	1.6	2.2	.80	.03

^aA denotes addition polymer; C denotes condensation polymer;

H denotes high modulus; L denotes low modulus.

^bJournal displacement was measured to the nearest 0.1 mil and converted to SI units.

^cEstimated.

TABLE IV. - WEAR DATA FOR A GRAPHITE-FIBER-REINFORCED
POLYIMIDE COMPOSITE WITH ADDITIVES

(a) SI units

Test temperature, °C	Additive to CH-type ^a GFRPI composite	After 2 kilo- cycles (run-in)	After 20 kilo- cycles (total)	0 - 2 kilo- cycles (run-in)	2 - 20 kilo- cycles (stabiliza- tion)
		Wear (as determined from journal displace- ment ^b), μm		Wear rate, $\mu\text{m}/\text{kilocycle}$	
25	None	48	51	24	0.2
	CdO	46	56	23	.6
	CdI ₂	36	36	18	<.2
	(CF _{1.1}) _n	25	38	13	.7
200	None	13	15	7	0.2
	CdO	33	33	17	<.2
	CdI ₂	33	41	17	.4
	(CF _{1.1}) _n	20	30	10	.6
315	None	43	56	22	0.7
	CdO	18	46	9	1.6
	CdI ₂	38	56	19	1.0
	(CF _{1.1}) _n	25	53	13	1.6

(b) U.S. customary units

Test temperature, °F	Additive to CH-type ^a GFRPI composite	After 2 kilo- cycles (run-in)	After 20 kilo- cycles (total)	0 - 2 kilo- cycles (run-in)	0 - 20 kilo- cycles (stabiliza- tion)
		Wear (as determined from journal displace- ment ^b), mil		Wear rate, mils/kilocycle	
85	None	1.9	2.0	0.95	0.006
	CdO	1.8	2.2	.90	.022
	CdI ₂	1.4	1.4	.70	<.005
	(CF _{1.1}) _n	1.0	1.5	.50	.028
400	None	0.5	0.6	0.25	0.006
	CdO	1.3	1.3	.65	<.005
	CdI ₂	1.3	1.6	.65	.017
	(CF _{1.1}) _n	.8	1.2	.40	.022
600	None	1.7	2.2	0.85	0.028
	CdO	.7	1.8	.35	.061
	CdI ₂	1.5	2.2	.75	.039
	(CF _{1.1}) _n	1.0	2.1	.50	.061

^aCH denotes a condensation polymer with high-modulus graphite fiber.

^bJournal displacement was measured to the nearest 0.1 mil and converted to SI units.

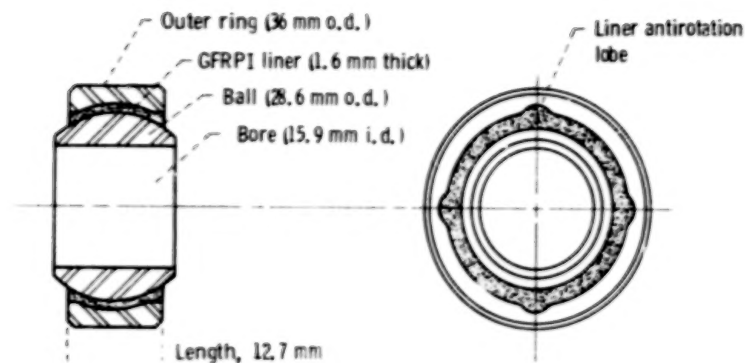


Figure 1. - Design of test bearing.

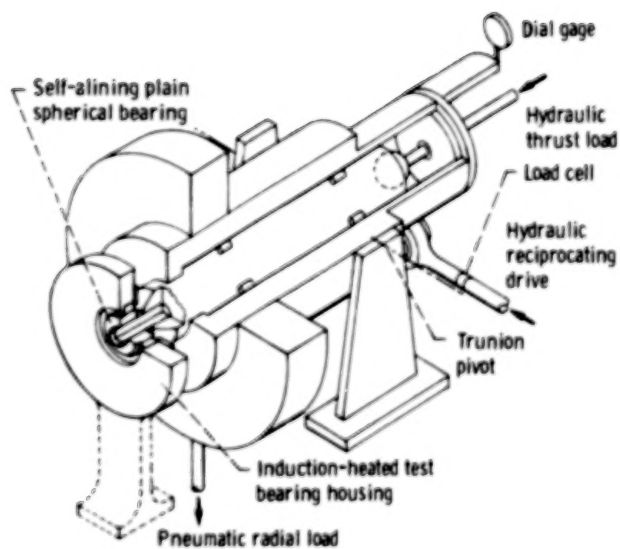


Figure 2. - Schematic of apparatus for testing self-aligning, plain spherical bearings.

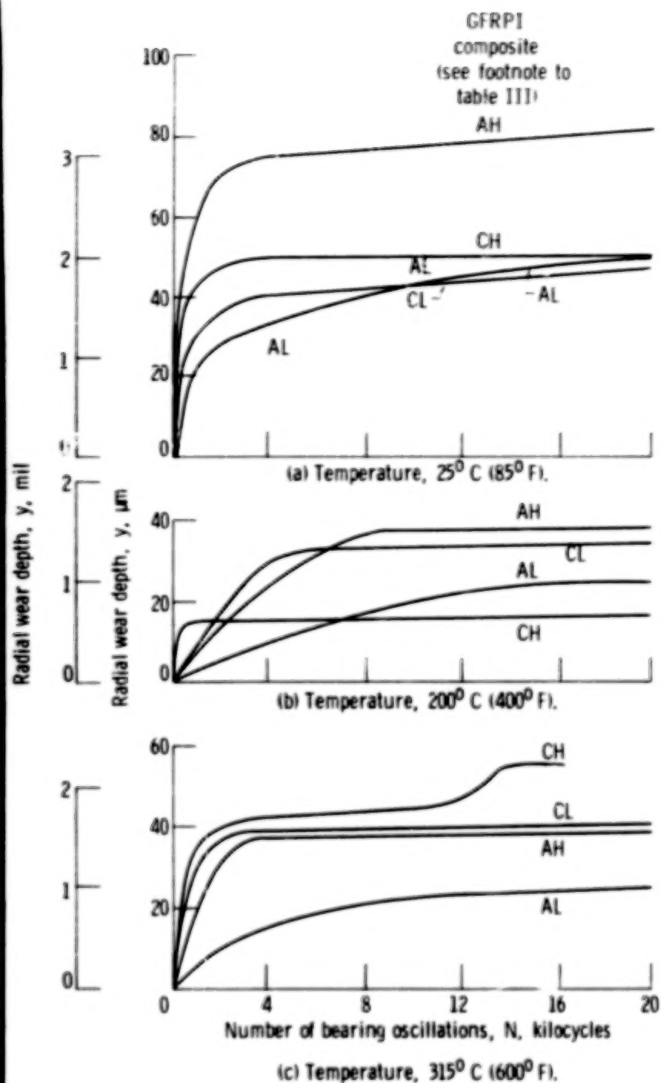


Figure 3 - Continuous wear characteristics of four graphite-fiber-reinforced composites. Unit load, $2.8 \times 10^7 \text{ N/m}^2$ (4000 psi); oscillation of ± 15 degrees at 1 hertz in dry air ($< 20\text{-ppm H}_2\text{O}$).

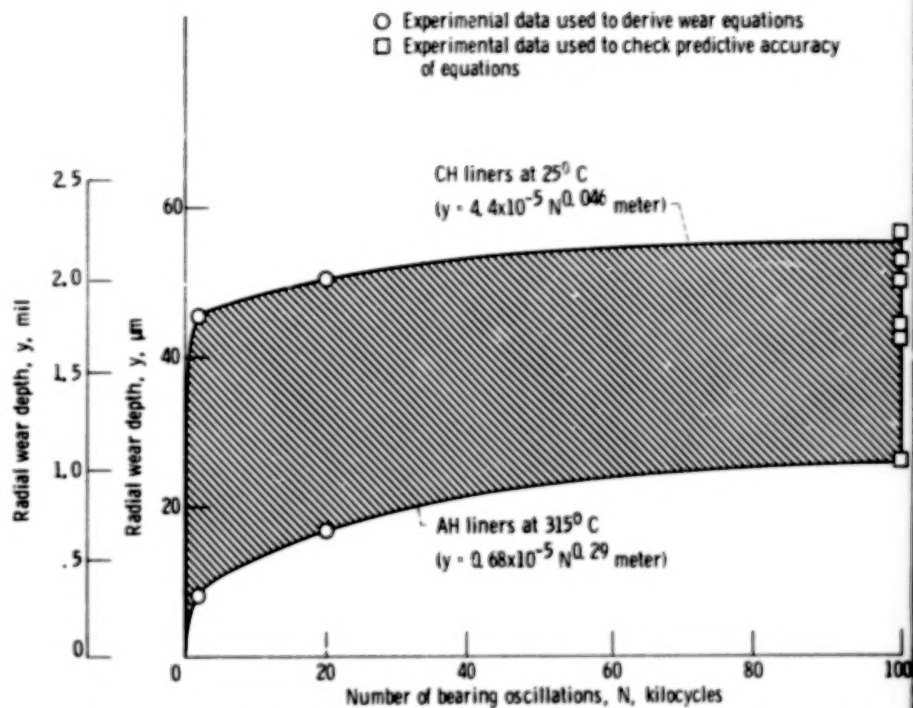


Figure 4 - Probable wear range for graphite-fiber-reinforced polyimide composite liners at temperatures from 25°C to 315°C and at a unit load of $2.8 \times 10^7 \text{ N/m}^2$ (4000 psi). (Constants for data fit equations calculated from experimental wear data at 2 and 20 kilocycles.)

GFRPI composite
(see footnote to
table III)

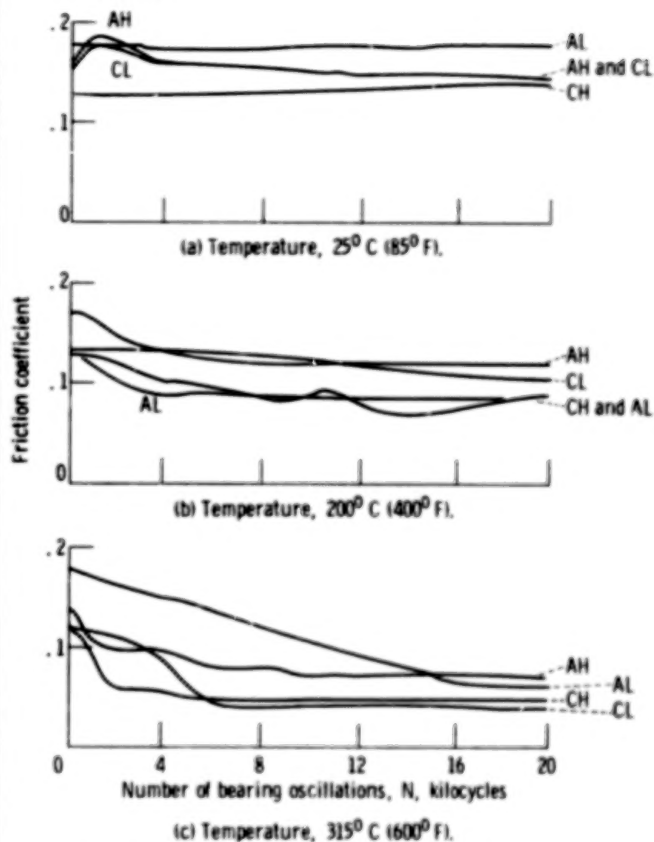


Figure 5. - Continuous friction characteristics of four graphite-fiber-reinforced polyimide composites. Unit load, $2.8 \times 10^4 \text{ N/m}^2$ (4000 psi); oscillation of ± 15 degrees at 1 hertz in dry air ($< 20\text{-ppm H}_2\text{O}$).

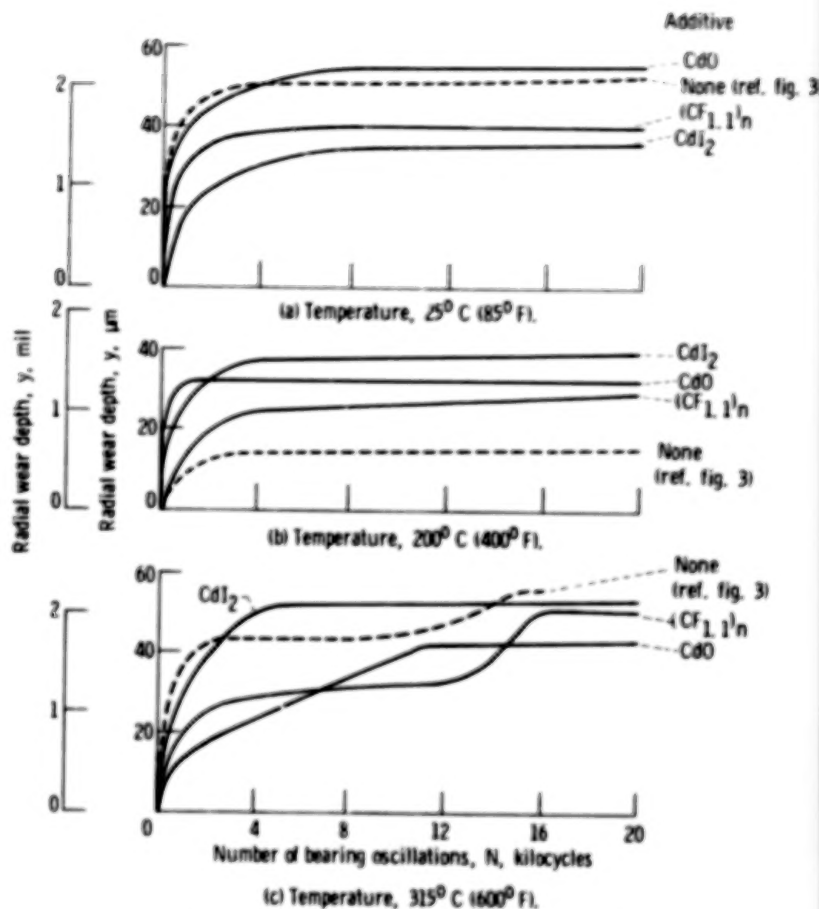


Figure 6. - Effect of 10-weight-percent additives on continuous wear characteristics of graphite-fiber-reinforced polyimide bearing liners made of condensation polymers with medium-tensile-strength and high-elastic-modulus fibers (CH composites). Unit load, $2.8 \times 10^4 \text{ N/m}^2$ (4000 psi); oscillation of ± 15 degrees at 1 hertz in dry air ($< 20\text{-ppm H}_2\text{O}$).

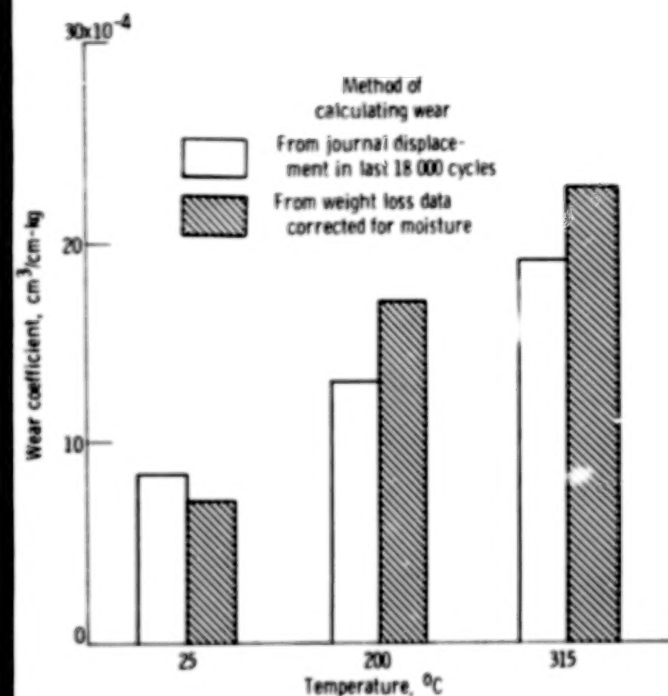


Figure 7. - Average wear coefficients for seven graphite-fiber-reinforced polyimide composites tested at 25°, 200°, and 315° C as outer-race liners in plain, spherical bearings. Unit load, 2.8×10^6 N/m² (4000 psi); oscillation of ± 15 degrees at 1 hertz in dry air (< 20 -ppm H₂O).

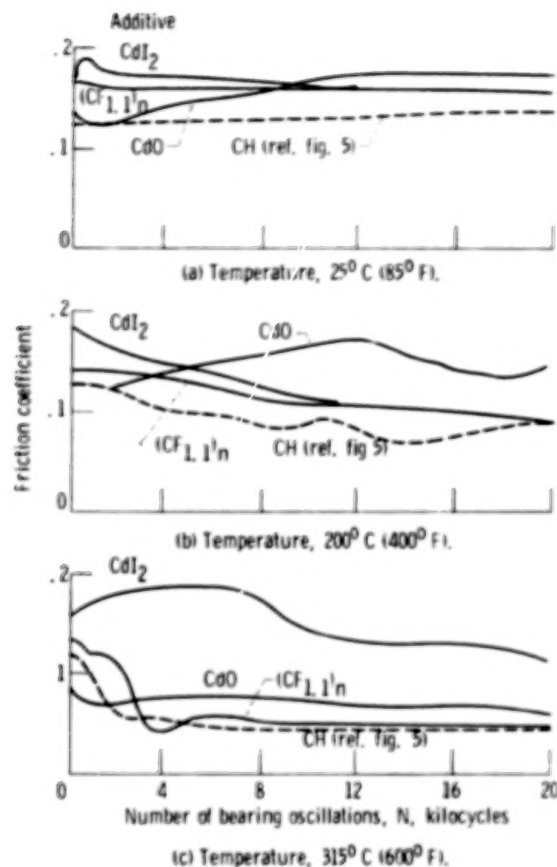


Figure 8. - Effect of 10-weight-percent additives on continuous friction characteristics of graphite-fiber-reinforced polyimide bearing liners made of condensation polymers with medium-tensile-strength and high-elastic-modulus fibers (CH composites).

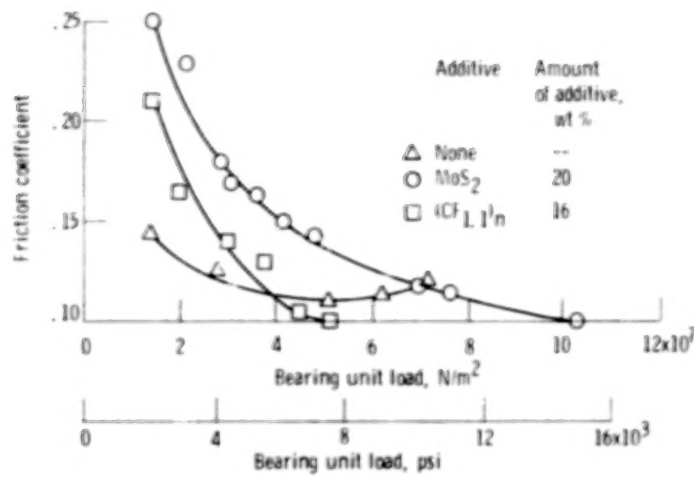


Figure 9 - Effects of load and additives on friction of as-received bearings. Test temperature, 25° C (85° F); relative humidity, 50 percent; oscillation of ± 15 degrees at 1 hertz.

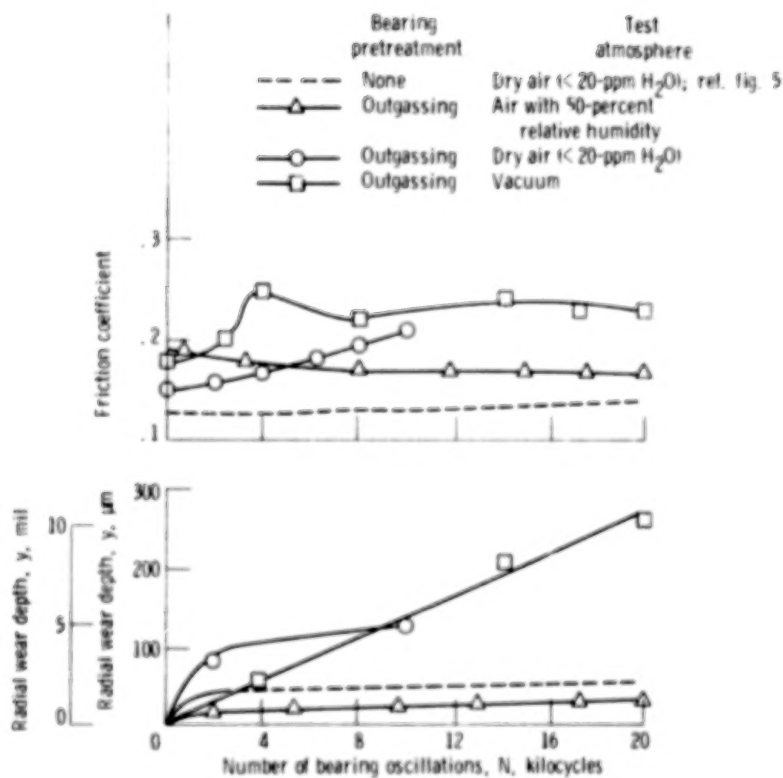


Figure 10 - Effects of bearing pretreatment and atmospheric moisture on friction and wear at 25° C (85° F).

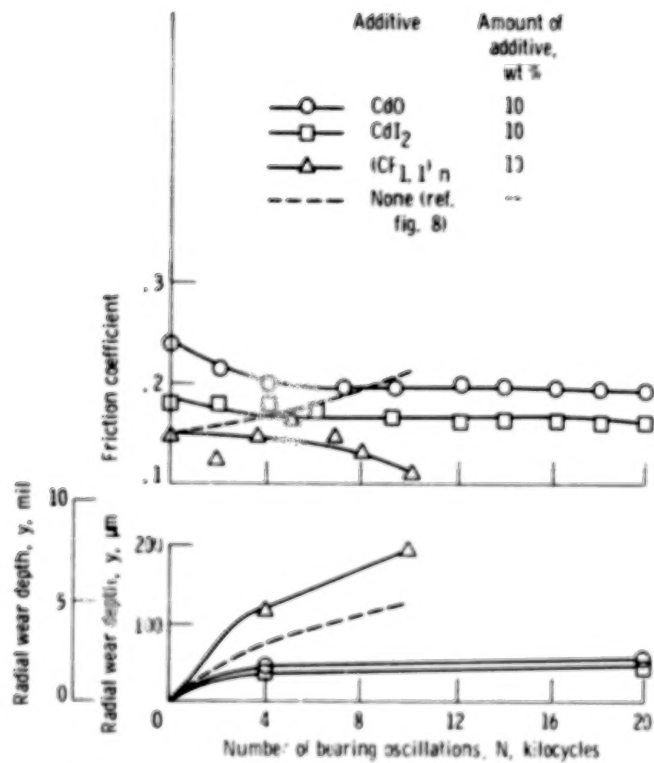


Figure 11. - Effect of additives on friction and wear of outgassed bearings. Test temperature, 25°C (85°F); dry air atmosphere, < 20-ppm H_2O .

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16 Abstract <p>Oscillating, plain spherical bearings with graphite-fiber-reinforced polyimide (GFRPI) liners were tested for friction and wear from 25⁰ to 315⁰ C. A condensation polymer was compared with an addition polymer, and a high-modulus fiber was compared with a lower cost, low-modulus fiber. All polymer-fiber combinations gave friction coefficients from 0.05 to 0.18 and low wear. Adding CdO and CdI₂ reduced the wear of degassed bearings in dry air. These additives were not needed when the bearing liners contained adsorbed moisture. Although, at 25⁰ C, MoS₂ reduced the friction and wear of the base composite at unit loads above 7.0×10⁷ N/m² (10 000 psi), it had no beneficial effect at lighter loads.</p>			
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